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MONITORING SOIL REDISTRIBUTION PATTERNS USING SEQUENTIAL AERIAL PHOTOGRAPHS

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ABSTRACT

Various methods have been used to study soil redistribution in the Loam Belt of Belgium. These methods have had contrasting levels of spatial coverage and time-scale. Ideally, a technique to assess soil redistribution patterns should provide the determination of dense networks of X, Y and Z terrain coordinates (digital elevation models) at different time intervals. Sequential stereoscopic aerial photographs contain this information, which can be extracted with standard photogrammetric techniques. In this study, aerial photographs taken by the National Geographic Institute of Belgium in 1947 and 1991 were used to determine the soil redistribution pattern between these years. This was done by overlaying the two digital elevation models and subtracting the corresponding Z coordinate values (heights). The results indicate that most severe surface lowering occurs on the top of the hillslope and on the hillslope convexities. Important deposition occurs on the lowermost parts of the hillslope, in most hillslope concavities and in the topographically defined concentration line. The observed pattern differs markedly from that expected from water erosion processes, and suggests that the soil redistribution is dominated by tillage operations.

KEY WORDS aerial photographs; soil redistribution pattern; hillslope; soil erosion; tillage

INTRODUCTION

The movement or redistribution of soil within a cultivated catchment can be assessed using various methods. Several studies in the Belgian Loam Belt used the depth of truncation of soil profiles as an indication of the severity and spatial variability of soil redistribution rates in small cultivated catchments (Tavernier, 1949; Peeters, 1986; Goossens, 1987). Other studies were based on the amount of material deposited as colluvium in valley bottoms (Bollinne, 1982).

Since the end of the 1970s, assessment of soil erosion rates and controlling factors have been restricted mainly to small experimental plots and fields (Bollinne, 1982; Govers, 1991). Recently, erosion surveys at a catchment scale have been done by Auzet *et al.* (1993) in northern France, Vandaele & Poesen (1995) in central Belgium and Schaub (1989) in Switzerland. In these studies, volumetric measurements of eroded volumes were used to assess soil losses. However, ground surveying techniques to assess soil erosion are very time-consuming and labour intensive so that such studies are only carried out over relatively short time periods. Therefore, there is a lack of data concerning erosion patterns and rates over longer time spans, e.g. 50 years. At present, only the caesium-137 technique is regularly used to assess the variability

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of erosion and sedimentation over the last 35 years (Vanden Berghe and Gulinck, 1987; de Roo, 1991; Quine *et al.*, 1994).

Another possibility for assessing soil redistribution over longer time spans is the use of time series of stereoscopic aerial photographs: these contain the necessary topographical information which can be extracted with standard photogrammetric techniques. Aerial photographs have already been used to detect soil erosion processes (Frazier and McCool, 1981; Frazier *et al.*, 1983; ADEPRINA, 1990). Information about the evolution of land use, field sizes, slope gradient, slope length and upstream area was extracted from sequential aerial photographs by the French Institut Géographique National to identify the zones within a small cultivated catchment (65 ha) with high erosion risks (IGN, 1982). A number of researchers in the United States have used photo-interpretation techniques to assess qualitatively cropland erosion from aerial photographs (Morgan *et al.*, 1980; Morgan & Nalepa, 1982; Stephens *et al.*, 1985; Whiting *et al*, 1987). Several other studies, however, have shown that sequential, large-scale aerial photographs can be used to derive quantitative measurements of ephemeral gully erosion from fields and small catchments (Welch and Jordan, 1983; Welch *et al.*, 1984; Spomer and Mahurin, 1984; Thomas *et al.*, 1986; Welch and Thomas, 1985). They have also shown that large-scale photogrammetric mapping offers a rapid method for measuring ephemeral gully erosion on a storm, seasonal or annual basis. Dymond and Hicks (1986) employed historical and recent aerial photographs to derive the volume of material lost or deposited within a mountainous catchment in New Zealand.

For many countries, various series of stereoscopic aerial photographs (which were taken for topographic mapping) are available, albeit at rather small scales. This study investigates to what extent these photographs can be used to identify the soil redistribution pattern over a longer time span within cultivated catchments.

MATERIALS AND METHODS

After the Second World War, photogrammetric mapping was introduced in Belgium. Aerial photographs from the years 1947 and 1949 were used to establish new large-scale topographical maps. Since then, most parts of Belgium have been photographed regularly, about once every 5 to 10 years. The aerial photographs were taken with standard photogrammetric mapping cameras ($f = 152$ mm) from altitudes of 1800 to 2400 m above terrain. Photography scale has varied between 1/25 000 and 1/8000. In this study we used two aerial photographic surveys, one carried out in 1947 at a scale of *c.* 1/20 000, and the other in 1991 at a scale of *c* 1/18 000.

The study field (*c.* 6 ha) is located in Korbeek-Dijle, in the loamy, hilly region between Leuven and Brussel, 3 km southwest of Leuven. The field occupies a south-facing slope and has a northwest-southeast orientated, well defined hollow. Historical maps indicate that the site was already deforested at the end of the 18th century. From 1960 to 1991, crops on the site were dominantly conventionally tilled winter cereals, potatoes, sugar beets and maize. The field was tilled more or less along the contour lines.

Photogrammetric analysis to obtain accurate terrain coordinates of the study site was done with an analytical restitution apparatus (Zeiss C-140 stereoplotter) by the National Geographic Institute of Belgium. All measurements were undertaken by a highly skilled photogrammetrist. Each stereo pair was orientated and positioned based on control points resulting from aerial triangulation. For each of the two aerial surveys, *c.* 700 to 1000 randomly chosen points on the soil surface together, with some feature-specific points (i.e. points along breaklines), were measured and the values of X, Y and Z coordinates were recorded. The combined use of randomly chosen and feature-specific points (i.e. along breaklines) very much improves the accuracy of the resulting digital elevation model (Li, 1994; Fryer *et al.*, 1994). The two sets of aerial photographs were treated in the same way and by the same person to avoid errors in the results due to different procedures. A series of large-scale topographic maps with contour intervals of 1 m (Figures 1 and 2) were established based on a triangulated irregular network (TIN). This TIN is generated from the measured points and consists of a series of triangular surfaces describing the surface of the terrain. This was done by using the CONTOUR module of the SDR software package based on linear interpolation (Datacom Software Research Ltd, 1989).

Next, a grid-based digital elevation model (DEM) was constructed. Interpolation was carried out using the G3GRID procedure with the linear interpolation option (SAS Institute, 1993). A horizontal resolution

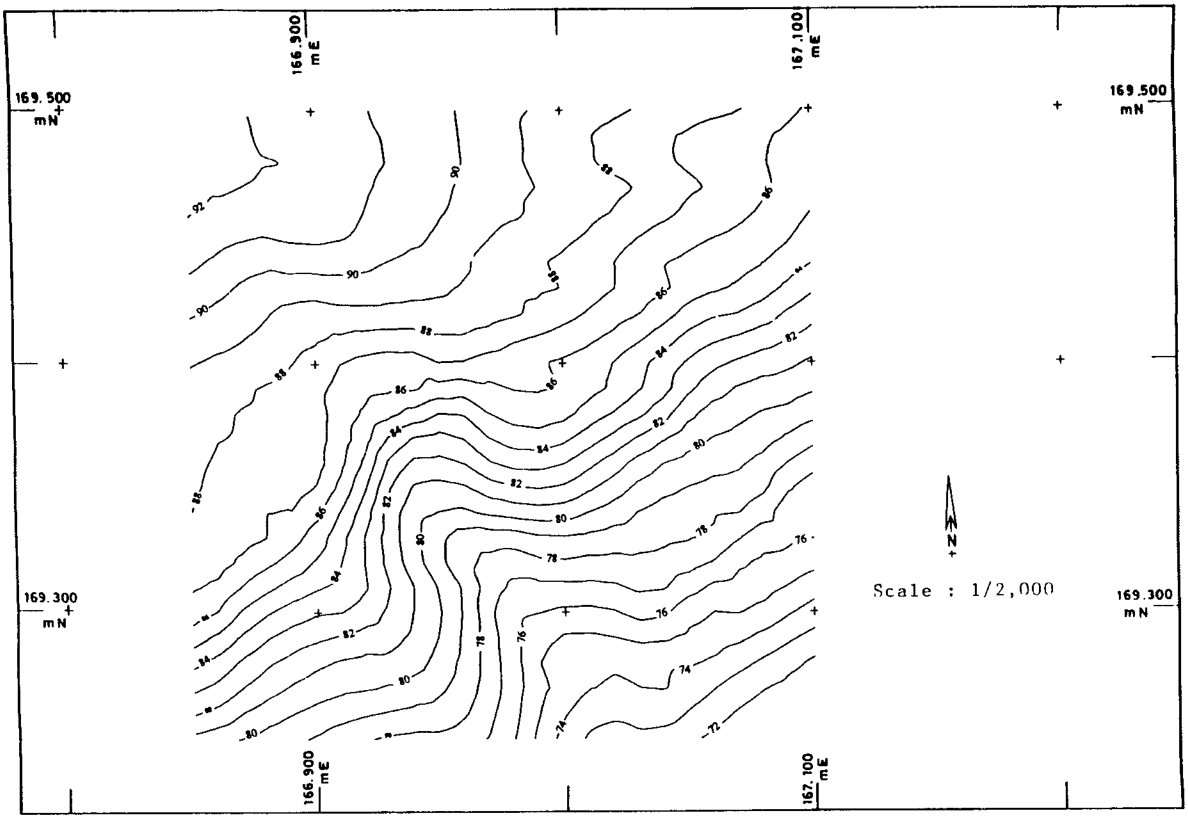

Figure 1. Contour map of the study area in 1947

of 10 m was used as the mean average distance between the original data points. The resulting three-dimensional perspective plots of the study field in 1947 and 1991 (based on a DEM) are shown in Figures 3 and 4.

The accuracy of the Z coordinate values is the critical parameter for soil erosion studies and must be so low that it can detect differences in heights between different time intervals. The time interval between two surveys, rate of soil redistribution, soil bulk density, inherent limits of photogrammetric measurements, and quality of equipment will affect the accuracy of the procedure (Spomer and Mahurin, 1984). In photogrammetric applications, the accuracy of spot heights is normally specified as root-mean-square (RMS) error, a statistical measure indication that 68 per cent of the coordinates are correct to within the specific value. When vertical photographs are recorded, the RMS error is often determined by the geometry of the camera set-up and vertical distance (H) from camera station to the ground. In this study, the accuracy of the height measurements resulting from photogrammetric analysis is influenced by a random error (point is not visible) and by a systematic error (control points are based on aerial triangulation). Accuracy also varies with topography and vegetation cover. However, owing to the fact that the study area is characterized by a gentle topography and is covered by one single crop, this variation will be small.

The RMS error of photogrammetrically measured elevation values was evaluated by the National Geographic Institute. They compared the Z values of individual points obtained with photogrammetrical analysis with those of field measurements (for the region of Brussels) and conclude that the RMS error of the Z coordinate measurements is about 0·5 m (National Geographic Institute, personal communication). Based on literature and own experience, Fryer *et al.* (1994) state that the achievable accuracy of Z values using aerial photographs ranges between 2 and 3 per 10 000 of the flying height. This means that for the study

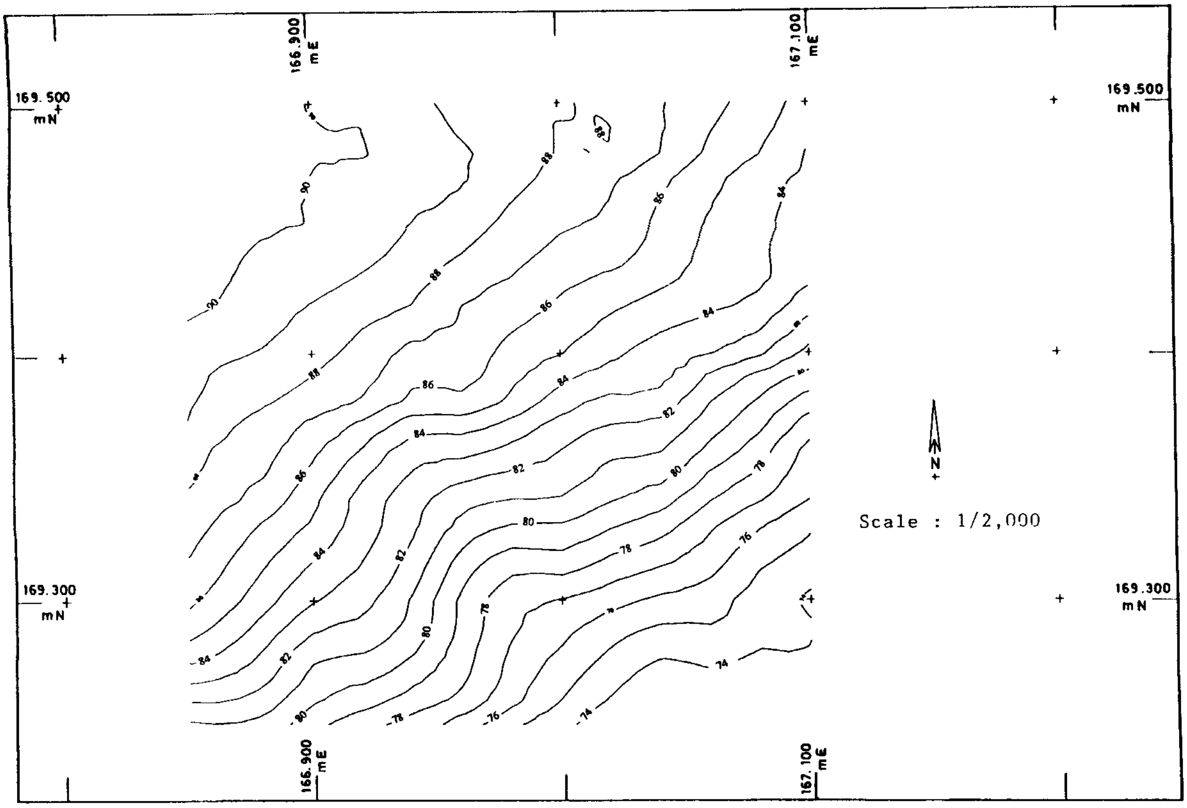

Figure 2. Contour map of the study area in 1991

area, the height of the Z values can be determined with an accuracy ranging between 0·36 and 0·72 m. This corresponds very well with our findings.

RESULTS

A shift in the planimetric position of a contour line on one map compared to the other indicates a change in elevation. A decrease in surface elevation (Z coordinate) will shift the contour lines uphill. Consequently, a shift of the contour lines downhill between the two aerial photographs indicates deposition. Comparing the contour maps of 1947 and 1991 it is striking that considerable deposition has occurred in the central drainage line (hollow or thalweg) since 1947 (Figure 5). Surface lowering is dominantly on the uppermost part of the field and on the convexities. The horizontal migration of the contour line multiplied by the local slope gradient (tangents) of the surface can then be used to calculate the surface lowering or aggradation (Spomer and Mahurin, 1984; Thomas *et al.*, 1986; Thomas and Welch, 1988). However, this procedure is very hard to handle with the available software packages and is also very time-consuming (Spomer & Mahurin, 1984).

Changes in surface elevation can also be determined by overlaying the 1991 DEM and the 1947 DEM and subtracting the corresponding Z coordinate (height) values (Welch and Thomas, 1985). This technique is known as 'image differencing' (Singh, 1989). The observed differences give information about the spatial distribution and rates of surface aggradation and lowering spots within the study field. Image differencing is the most widely used technique for change detection and has been used in a variety of geographical environments (Eastman, 1992; Singh, 1989).

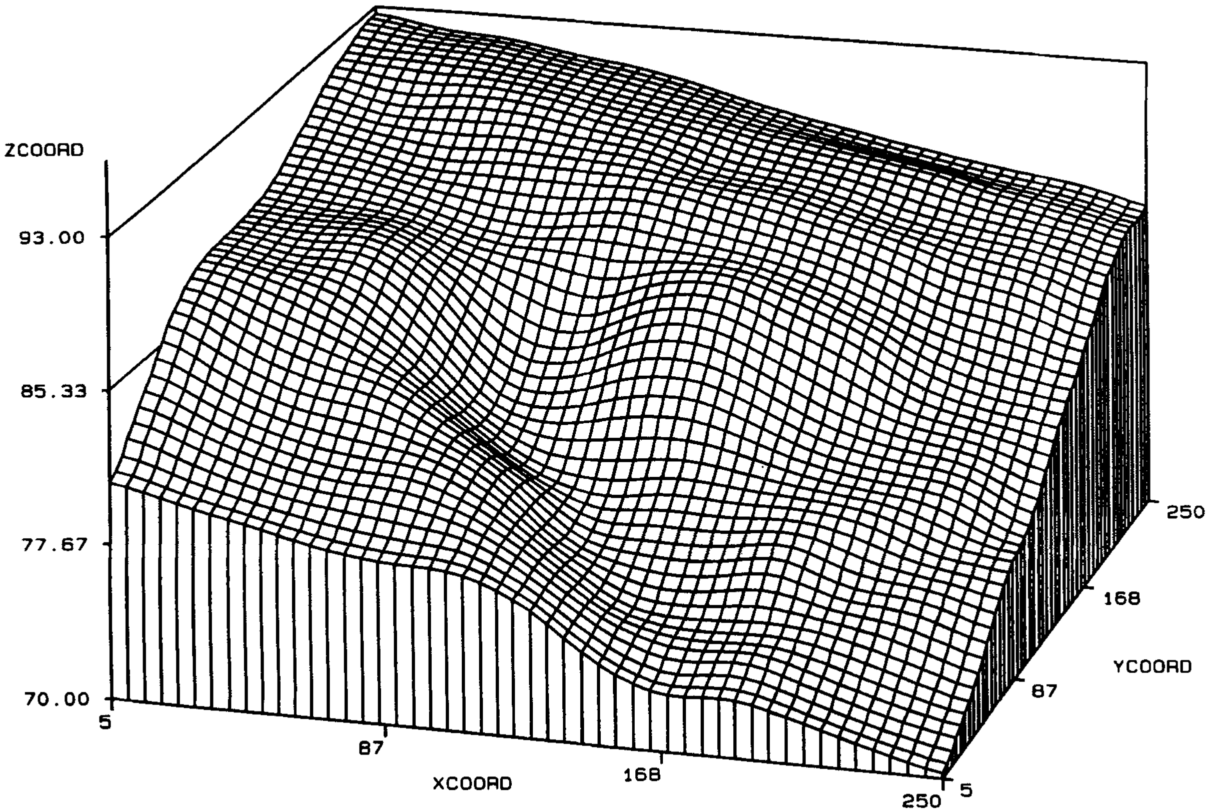

Figure 3. Three-dimensional perspective plot of the study area in 1947

In order to establish threshold values to detect significant differences, the RMS error limit of the differences in Z values (heights) was used. The latter is calculated as $\sqrt{e_1{}^2 + e_2{}^2}$, where e^i is the RMS error limit of the individual Z coordinate value (height) measurements for 1947 and 1991. Above, it was stated that the vertical accuracy or RMS error of the photogrammetrically measured Z values was *c.* 0·5 m. This means that the RMS error of the individual differences in height is equal to 0·7 m. Threshold values of $\pm N$ times the RMS error limits from the Z value differences between 1947 and 1991 were selected to separate the change from no-change pixels (Table I). Taking this information into account, we can construct a map separating the change from the no-change areas within the field (Figure 6).

Table I. Significance level of the differences in height (ΔZ) defined by N times the RMS error limit (σ). In this study $\sigma = 0{\cdot}7$ m

Differences in height (ΔZ)	Significance level
$\Delta Z < -1{\cdot}65\sigma$ or $\Delta Z > 1{\cdot}65\sigma$	$\pm 0{\cdot}100$
$\Delta Z < -2{\cdot}0\sigma$ or $\Delta Z > 2{\cdot}0\sigma$	$\pm 0{\cdot}050$
$\Delta Z < -3{\cdot}0\sigma$ or $\Delta Z > 3{\cdot}0\sigma$	$\pm 0{\cdot}003$
$\Delta Z < -4{\cdot}0\sigma$ or $\Delta Z > 4{\cdot}0\sigma$	$<0{\cdot}001$

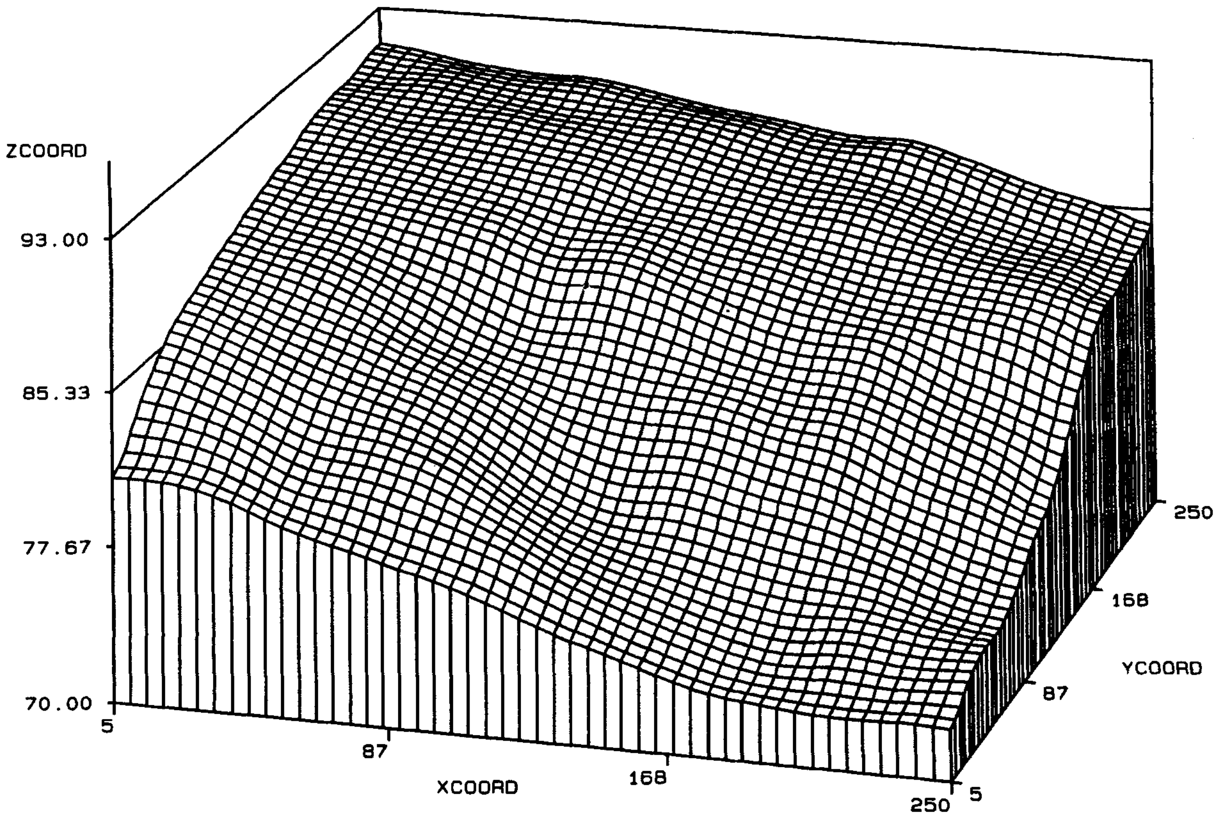

Figure 4. Three-dimensional perspective plot of the study area in 1991

The redistribution pattern derived from image differencing is very similar to that indicated by contour line migration, i.e. deposition in the main thalweg and surface lowering on the upper slopes and convexities. Furthermore, based on the DEM of 1947 we can calculate the vertical curvature (C_v). The vertical curvature is the curvature of the drainage line (the line of maximum slope) and is an objective measure of slope gradient change along this line. C_v is calculated using the digital relief model 'BORK' and can be used to subdivide the field into different morphological areas (Bauer *et al.*, 1985; Bauer, 1988). Bauer distinguishes between hillslope convexities ($C_v < -0{\cdot}005$), concavities ($C_v > 0{\cdot}005$) and linear hillslope segments ($-0{\cdot}005 \leq C_v \leq 0{\cdot}005$). To study whether or not the mean differences in elevation for each morphological

Table II. Mean elevation changes for the concave, convex and linear hillslope segments. Analysis of variance was carried out using the SAS procedure GLM (SAS Institute, 1985). Differences between means were tested on significance level ($P < 0{\cdot}001$) using the Bonferronni T-Test

Morphological area	Elevation change (m)	Means with the same letter are not significantly different
Concave slope segments	0·40	A
Linear slope segments	−0·28	B
Convex slope segments	−0·58	C

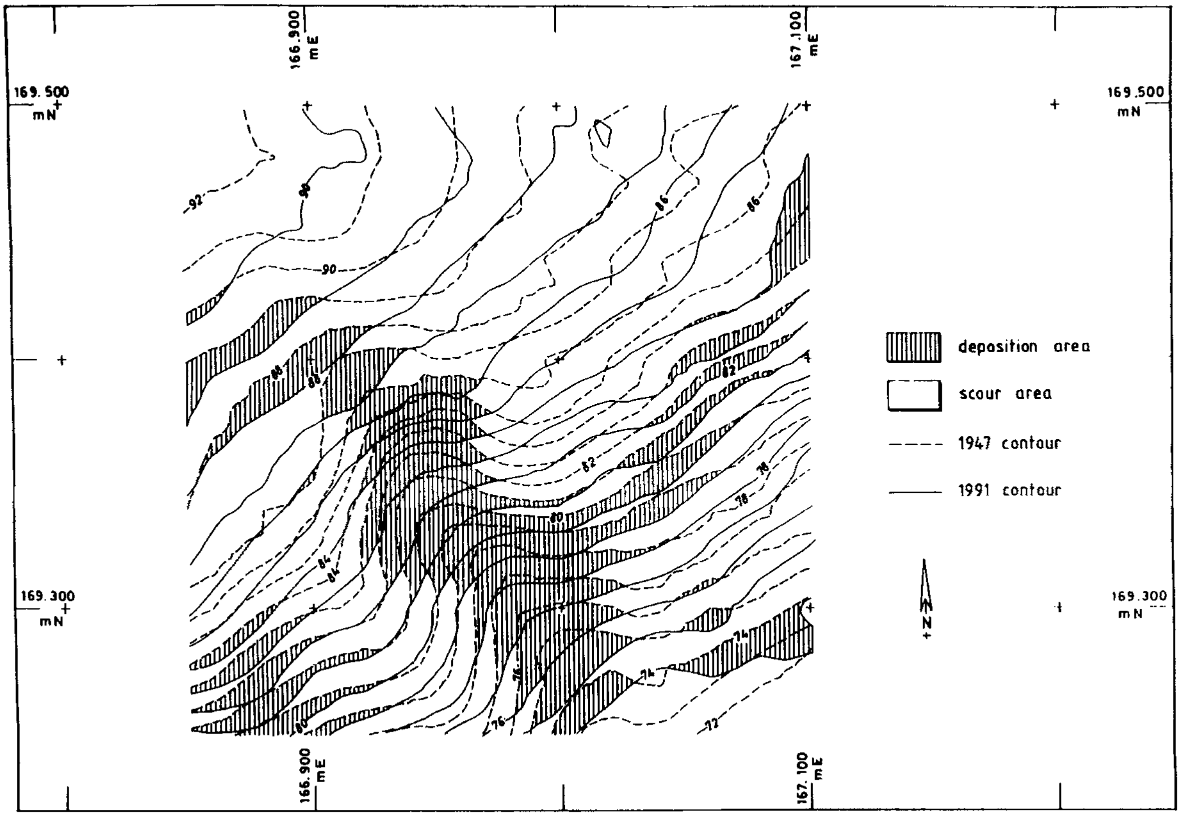

Figure 5. Soil redistribution pattern between 1947 and 1991 based on the contour maps

area are significantly different, an analysis of variance was carried out using the SAS procedure GLM (SAS Institute, 1985). The results (Table II) clearly show that concavities and convexities have significantly different elevation changes. The concave hillslope segments are characterized by surface aggradation (mean value = 0·40 m) while the convex parts are characterized by surface lowering (mean value = −0·58 m). Linear hillslope segments also show a surface lowering (mean value = −0·28 m).

The systematic variation of height differences with topographical characteristics implies that measured height differences cannot be explained by random errors in the photogrammetric analysis. Indeed, if the latter was the case, errors should be randomly distributed over the surface considered. On the other hand, it is possible that a relatively small systematic error is present, but this will only have a minor effect on the derived soil redistribution pattern.

DISCUSSION

Water and tillage operations are identified in the literature as important soil redistribution processes. Soil erosion by water is frequent and widespread in the Belgian Loam Belt and can be defined as the detachment and transport of soil particles due to the erosive force of runoff (overland flow). Different types of erosion by water can be identified: (1) splash erosion (Bollinne, 1978; Poesen, 1986); (2) rill–interrill erosion (Gabriels *et al.*, 1977; Bollinne, 1982; Govers and Poesen, 1988); and (3) erosion by concentrated water (ephemeral gullies and gullies associated with banks) (Poesen and Govers, 1990; Vandaele and Poesen, 1995). These erosion features are easily removed by tillage. On the other hand, tillage operations (i.e. moulboard ploughing)

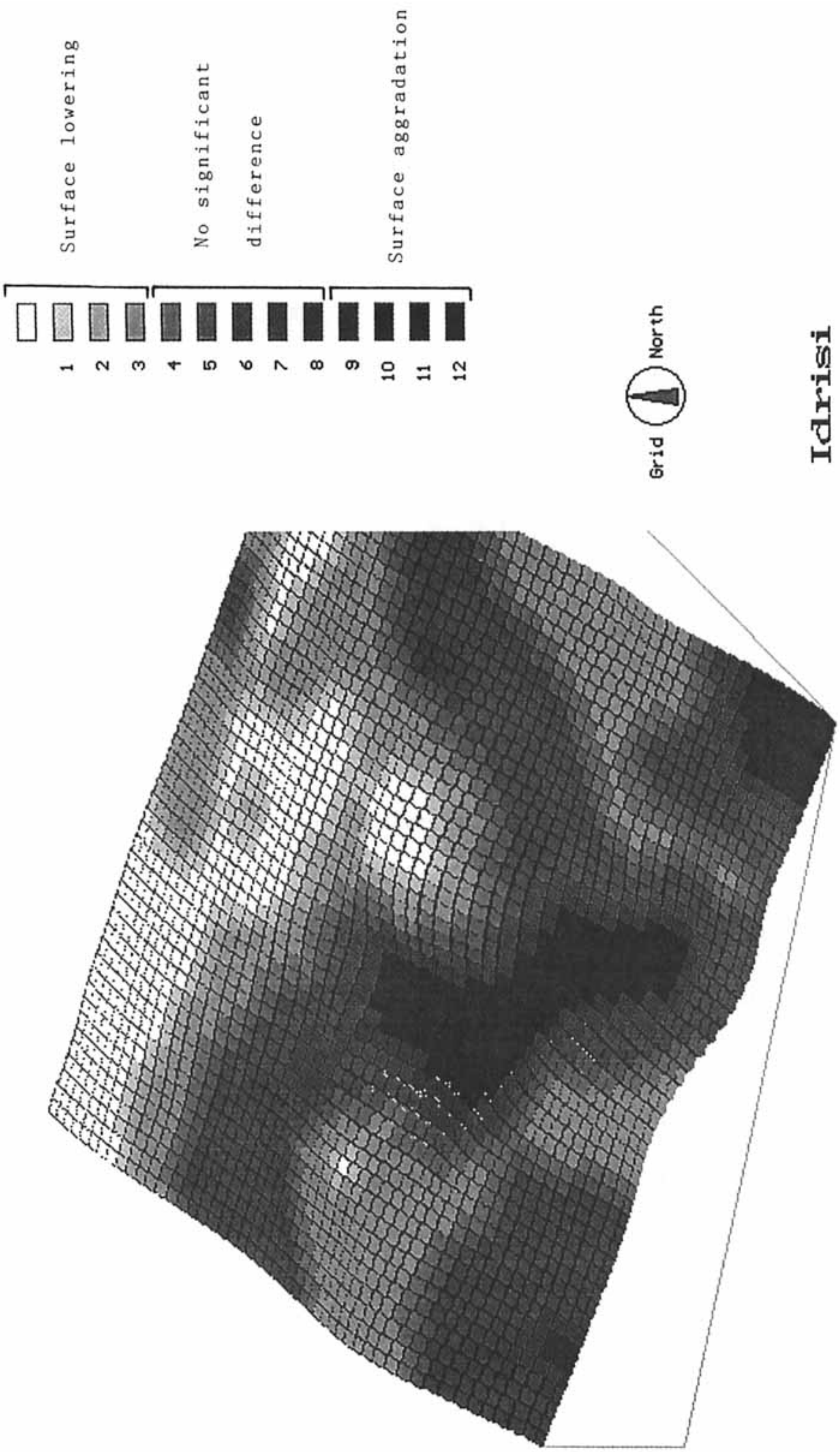

Figure 6. Soil redistribution pattern between 1947 and 1991 based on Digital Elevation Models

will also reverse and shift the tillage horizon over a distance of at least 0·3 m. Whether the field is tilled up- and downslope or across-slope, the downslope movement of soil due to ploughing is not compensated by the uphill movement (Govers *et al.*, 1994). This can cause a net downslope displacement of an important part of the tillage horizon within the field. Each of these processes will produce a typical soil redistribution pattern. In this section we compare the observed redistribution pattern on our study field with the patterns suggested by water erosion and tillage operations.

In the Belgian Loam Belt, soil erosion is a well known problem, causing a lot of soil loss on the fields but also floods and massive sedimentation in villages situated downstream. Recent field observations indicate that the surface lowering and aggradation due to rill and interrill erosion can be modelled as a power function of slope angle and length (Govers, 1991; Govers *et al.*, 1993). This implies that water erosion will be most intense on the steepest and/or lowermost parts of the hillslopes (Govers *et al.*, 1993). However, this work does not consider soil loss due to concentrated flow in topographically defined flow paths. Measurements made by Vandaele (1993) and Vandaele and Poesen (1995) during a 3-year period in three small cultivated catchments indicate that almost 50 per cent of total soil loss occurs in these topographically defined flow-paths. This means that ephemeral gully erosion is an important sediment source. Vandaele and Poesen (1995) also found that there was no (or very small) net accumulation of sediment in the upper dry valley network within the catchments. Similar situations were also described by Auzet *et al.* (1993) in northern France, and Baade *et al.* (1993) in Germany. In effect, from aerial photographs taken in 1963, 1981 and 1986, ephemeral gully erosion can be observed in the main topographically defined flow-path (hollow) of our study field. Furthermore, gully erosion in the hollow was monitored by volumetric measurements from October 1989 to October 1992. Over this period a total net soil loss of *c.* 30 m^3 was recorded.

Summarizing all this information we can conclude that water erosion is lowest on the top of the hillslope, and most severe on the steepest slopes and also on the lower parts of the slopes. Also, severe erosion will occur in the upper dry valley network. The lower dry valley network is characterized by important sedimentation.

However, the redistribution pattern observed from the aerial photographs indicates that the most severe surface lowering took place on the upper hillslopes and convexities, while important deposition occurred on the lowermost parts of the field, the concavities and in the hollow. Thus, the observed soil redistribution pattern cannot be explained by the activity of water erosion processes alone.

The role of tillage operations in soil redistribution has already been mentioned in several publications (Melard, 1969; Bollinne, 1971; Papendick and Miller, 1977). Mellard (1969) found that the downslope shift of material due to ploughing could construct accumulation zones at the downslope field border of about 1–1·5 m depth (lynchets) within less than 100 years. Bollinne (1971) found an accumulation of 0·25 m during a 20-year period due to combined water and tillage depositions. Thomas *et al.* (1988) found that more material was tilled by the farmer into the topographically defined concentration line than was eroded from two major gullies situated in the same thalweg.

Recent experiments give more information about the soil redistribution pattern due to tillage and show that soil tillage can cause an important net downslope movement of soil within a field (Lindstrom *et al.*, 1992; Revel *et al.*, 1993; Govers *et al.*, 1993, 1994). Govers *et al.* (1994) suggest that the soil redistribution by tillage (soil flux) can be described by a diffusion-type equation. This implies that, in principle, tillage erosion and deposition are controlled by slope gradient change and not by absolute values of slope length and gradient. Consequently, erosion will take place on the convexities, while sedimentation occurs on the concavities. Also, field boundaries will be lines of zero flux, so that important sedimentation will take place on the upslope side while erosion will occur on the downslope side.

On our study site we observe that the most important surface lowering takes place on the hillslope convexities, while sedimentation takes place in the hollow and on the lowermost concave parts of the hillslopes. Thus, there is good agreement between the observed pattern of soil redistribution and the pattern suggested by soil tillage operations. This result suggests that there is strong evidence for an important effect of soil tillage on the redistribution of soil material and the evolution of topography during the last 44 years.

It is interesting to compare these results with those from soil truncation studies. Soil truncation and burial are the result of soil redistribution since land clearance. Several studies indicate that heavily truncated soils

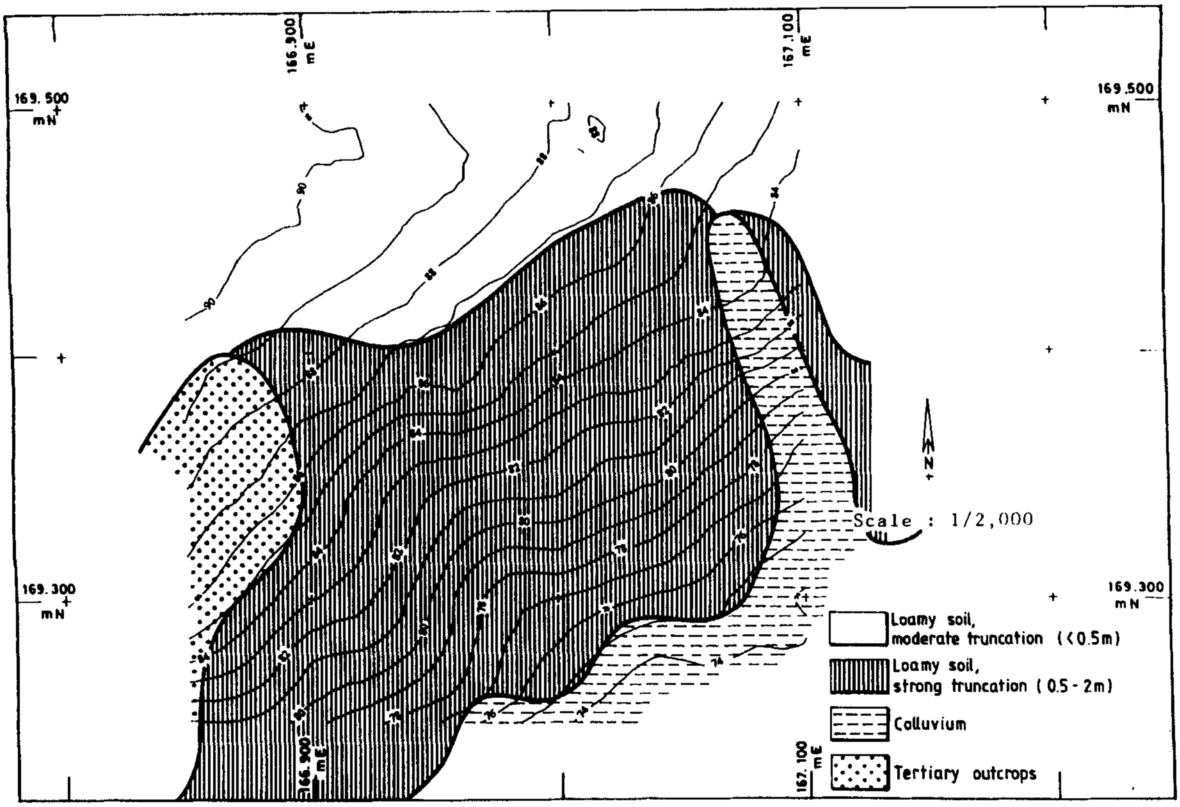

Figure 7. Simplified soil and contour map of the study area

are abundant in the Belgian Loam Belt, and are situated mainly on the steepest slope segments as well as on many lower parts of the slopes (Tavernier, 1949; Peeters, 1986; Goossens, 1987). This general pattern is also present in our study area. On the soil map of Belgium, the upper part of the field (northern part) is indicated as slightly truncated, the slopes as highly eroded and the lowermost parts of the field are covered by important colluvial deposits. Also, the soil in the main concentration line is identified as highly truncated (Figure 7). This redistribution pattern closely corresponds with what can be expected from water erosion activity. However, the soil redistribution pattern derived from aerial photographs indicates that soil tillage has been dominant over the last 44 years. This suggests that an important shift in the relative importance of tillage and water erosion processes may have occurred: while soil redistribution appears to have been dominated by water erosion before agricultural mechanization, tillage erosion has become dominant over the last 50 years.

CONCLUSIONS

Aerial photographs with scales ranging between 1/15 000 and 1/25 000 can be used to determine the soil redistribution pattern over the last *c*. 50 years. If small-scale photographs are to be used, the technique can only be applied in areas where considerable soil redistribution is occurring. Only height differences exceeding several decimetres can be considered to be significant. The aerial photographic coverage in Belgium, as well as in many other European countries, is such that this technique can potentially be applied to most parts of Europe.

The soil redistribution pattern on the study site showed a systematic pattern. Significant surface lowering is found to occur on the uppermost part of the field and also on most convexities. On the other hand, significant surface aggradation is observed in the topographically defined concentration line (hollow) and on the downslope part of the field.

The observed soil redistribution pattern differs markedly from that suggested by water erosion processes. On the other hand, there is good agreement between the observed pattern of soil redistribution and the pattern suggested by soil tillage operations. Thus, there is strong evidence that soil tillage is an important geomorphological process on arable land. A comparison with the truncation and burial patterns recorded on the Belgian soil map suggests that a major shift in the relative importance of tillage erosion and water erosion processes may have occurred since the mechanization of agriculture.

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